

# Ubiquitous equatorial accretion disc winds in black hole soft states

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## ABSTRACT

High resolution spectra of Galactic Black Holes (GBH) reveal the presence of highly ionised absorbers. In one GBH, accreting close to the Eddington limit for more than a decade, a powerful accretion disc wind is observed to be present in softer X-ray states and it has been suggested that it can carry away enough mass and energy to quench the radio jet. Here we report that these winds, which may have mass outflow rates of the order of the inner accretion rate or higher, are an ubiquitous component of the jet-free soft states of all GBH. We furthermore demonstrate that these winds have an equatorial geometry with opening angles of few tens of degrees, and so are only observed in sources in which the disc is inclined at a large angle to the line of sight. The decrease in Fe XXV/ / Fe XXVI line ratio with Compton temperature, observed in the soft state, suggests a link between higher wind ionisation and harder spectral shapes. Although the physical interaction between the wind, accretion flow and jet is still not fully understood, the mass flux and power of these winds, and their presence ubiquitously during the soft X-ray states suggests they are fundamental components of the accretion phenomenon.

**Key words:** black hole physics, X-rays: binaries, absorption lines, accretion, accretion discs, methods: observational, techniques: spectroscopic

## 1 INTRODUCTION

The feedback of liberated gravitational potential energy by accreting black holes is determined by the combination of accretion states and outflow modes. In galactic black holes (GBH), hysteresis is observed between the X-ray state of the accretion flow, which is strongly coupled to the presence of a relativistic jet, and the luminosity of the source (Fender et al. 2004). The jet is always present in ‘hard’ X-ray states, which can be observed at all luminosities. However, at the highest luminosities sources can enter into a ‘soft’ X-ray state in which the jet is switched off and kinetic feedback therefore appears to be strongly suppressed. Once the soft state is entered, GBH remain in this state until they decline to  $\sim 1\%$  of the Eddington rate, at which point they return to the hard state. Interestingly, it has been suggested that similar states also apply to AGN (Koerding et al. 2006).

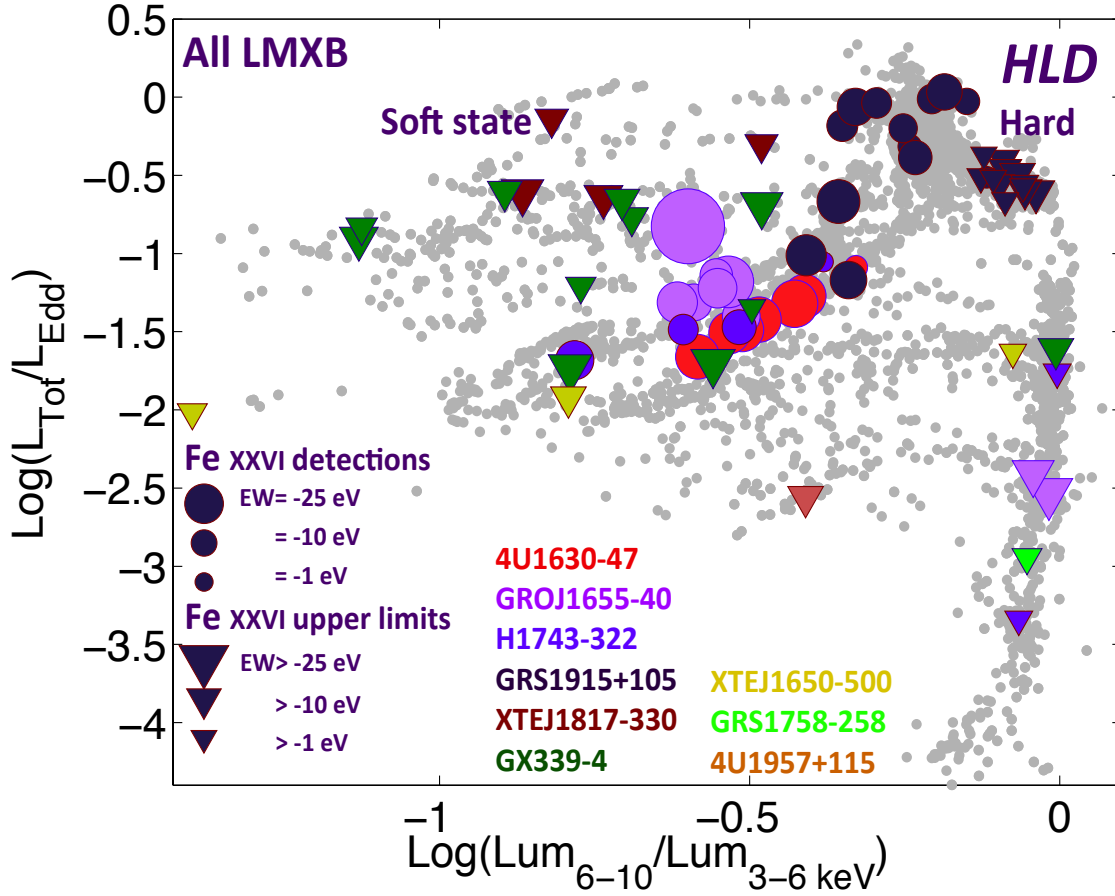
Recent high energy resolution observations of several GBH showed the presence of winds (Lee et al. 2002; Miller et al. 2004; 2006a,b), indicating that these objects drive outflows not only in the form of jets, but also of winds (Diaz-Trigo et al. 2011). There are three main mechanisms that can launch a wind from the surface (the atmosphere) of the accretion disc: thermal, radiation and magnetic pressure. In each case, a wind will be launched only if the pressure

can overcome gravity. As a rule of thumb, the closer the launching point is to the BH, the higher the wind terminal velocity.

In GRS1915+105, a peculiar GBH accreting close to the Eddington rate for more than a decade (Fender & Belloni 2004), an accretion disc wind appears to be present in softer X-ray states and to be so powerful and to carry away so much mass as to halt the flow of matter into the jet (Neilsen & Lee 2009).

## 2 WIND-STATE-JET CONNECTION

We have performed a comprehensive study of ionised X-ray winds in GBH. To do this, we analysed the X-ray spectra of all the *Chandra*, *XMM-Newton* and *Suzaku* observations of black hole Low Mass X-ray Binaries (LMXB, which are GBH accreting by Roche lobe overflow) with well studied outbursts (Dunn et al. 2010) and at least one deep (exposure  $> 5$  ks) grating spectroscopy observation. An effective way to separate the observations during the soft and hard states is to plot the Hardness Luminosity Diagram (HLD). We compute the HLD from data obtained with the Rossi X-ray Timing Explorer (*RXTE*) by first fitting each spectrum of each source with two components, a multi-temperature disc black body component for the disc and a power law component for the corona (see Dunn et



**Figure 1.** The presence or absence of ionised winds in a sample of GBH. The grey (background) points show the Hardness Luminosity Diagram (HLD) of all Low Mass X-ray Binaries (LMXB) studied. The hardness is computed from *RXTE* data as  $\text{Log}(\frac{L_{6-10}}{L_{3-6}})$ , where  $L_{6-10}$  and  $L_{3-6}$  are the source luminosity in the 6-10 and 3-6 keV bands, respectively. Circles indicate *Chandra*, *XMM-Newton* and *Suzaku* observations during which a high ionisation wind is detected through the observation of the Fe XXVI absorption line. The size of the symbol is directly proportional to the EW of the Fe XXVI absorption line. Triangles show, instead, the non-detections. Their size is proportional to the upper limit on the Fe XXVI EW. The different colors indicate data results from different sources. In soft states, during which the jet is always quenched, sometimes a wind is observed. However, other soft state observations show stringent upper limits on the presence of the wind.

al. 2010 for more details). The grey (background) points in Fig. 1 show the total luminosity (in Eddington units) vs. the hardness for each *RXTE* observation. The hardness is computed as  $\text{Log}(\frac{L_{6-10}}{L_{3-6}})$ , where  $L_{6-10}$  and  $L_{3-6}$  are the observed source luminosity in the 6-10 and 3-6 keV bands, respectively. During observations in the hard state, the spectrally hard power law component dominates the emission, thus  $\text{Log}(\frac{L_{6-10}}{L_{3-6}})$  is close to 0.

Circles in Fig. 1 correspond to each *Chandra*, *XMM-Newton* and *Suzaku* observations during which a high ionisation wind is detected through the observation of the Fe XXVI absorption line. In particular the size of the symbol is directly proportional to the EW of the Fe XXVI absorption line. Triangles, instead, report wind non-detections (symbol size proportional to the Fe XXVI upper limit).

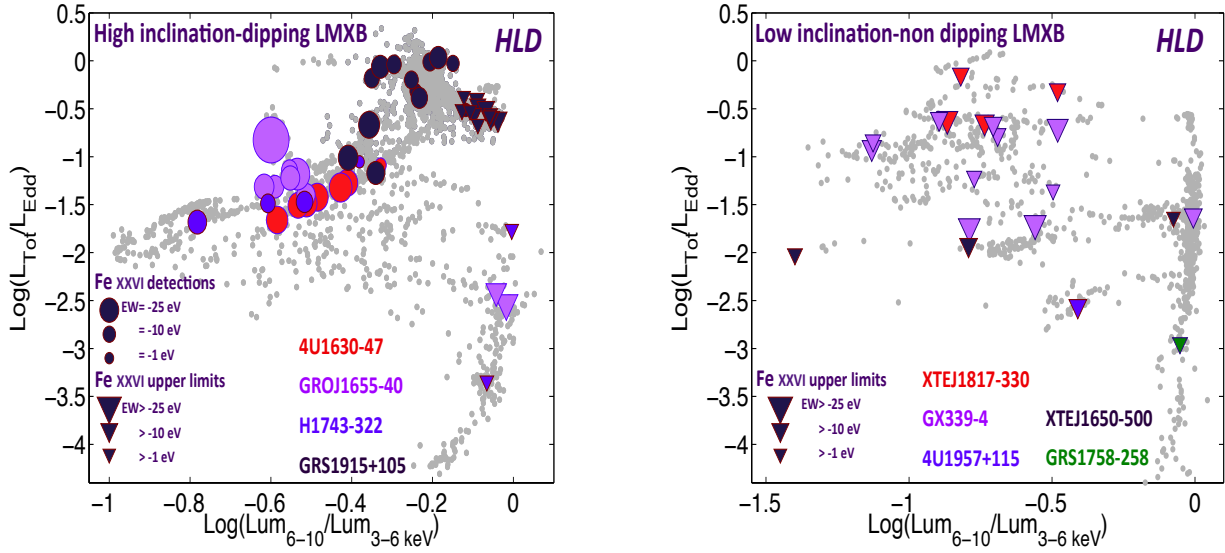
Analysing just 11 GRS1915+105 *Chandra* observations, Neilsen & Lee (2009) already measured a strong anti-correlation between the presence of the (radio) jet and of the winds, with the wind being present primarily during the jet-free soft states and disappearing during hard states (see also Miller et al. 2008). The

addition of the *XMM-Newton* and *Suzaku* data, which more than doubles the number of observations, confirms and strengthens the anti-correlation (with now a total of 26 good quality spectra) in this peculiar LMXB.

However, when we consider other LMXBs, the picture appears to be more complex. In fact, stringent upper limits are set during 17 soft state (jet-quenched) observations. In the next section, we suggest that this may be an effect of viewing geometry.

### 3 THE WIND ANGULAR DEPENDENCE

To study the wind angular dependence we aim at dividing the sources into two samples, based on inclination. Thanks to extensive campaigns at other wavelengths, we know that GROJ1655-40 and GRS1915+105 are high inclination sources, close to edge-on, with similar disc inclinations of  $\sim 70$  degrees (van der Hooft 1998; Greiner et al. 2001). GROJ1655-40 is also known to experience frequent dips (Tanaka et al. 2003). The dipping phenomenon is



**Figure 2.** (Left panel) HLD of the high inclination (dipping) LMXB studied and of all the low inclination (non dipping) LMXB, right panel. High inclination (dipping) sources show Fe XXVI absorption every time they are in the soft state and upper limits in the hard states. In low inclination (non dipping) LMXB the Fe XXVI absorption line is never detected. We interpret these as due to an ubiquitous equatorial disc wind associated with soft states only. We note that high inclination sources tend to show a more triangular HLD, while the low inclination sources exhibit a boxy one.

thought to be produced by clumps of low ionisation material along the line of sight, that are temporarily obscuring the X-ray source. The intervening material is probably related to the transfer of matter from the companion star to the disc and it generally occurs in sources observed at high inclination (Frank, King & Raine 2002). Therefore we also added H1743-322 and 4U1630-47, known to experience frequent dips (Homan et al. 2005; Tomsick et al. 1998), to represent a population of sources which are close to edge on. Fig. 2 (left panel) shows the HLD of all the high inclination LMXB and reports the measured Fe XXVI absorption line Equivalent Width (EW). These sources show clear evidence for a high ionisation disc wind ( $v_{\text{out}} \sim 10^{2.5-3.5} \text{ km s}^{-1}$ ) during all 30 observations in the soft state<sup>1</sup>.

On the other hand whenever these sources are observed in the hard X-ray state, they show only upper limits. We, in fact, observe stringent upper limits for 16 out of 17 observations and just one detection of a weak wind quasi-contemporaneous with a weak jet (Lee et al. 2002; Neilsen & Lee 2009). This demonstrate that for this set of sources the presence of the disc wind is deeply linked to the source state. In particular, the wind is present during spectrally-soft states, when the jet emission is strongly quenched.

The right panel of Fig. 2 shows the HLD for the non dipping LMXB, GX339-4, XTEJ1817-330, 4U1957+115, XTEJ1650-500 and GRS1758-258, which have accretion discs which are inclined more face-on to the observer. None of these source has a detection of a highly ionised wind in any state. Several spectra have a signal-to-noise ratio good enough to measure upper limits as small as a few eV, even during the soft state. For this reason, we confidently state that these sources do not present the signatures of highly ionised FeK winds<sup>2</sup>.

<sup>1</sup> One observation of GRS1915+105 with lower luminosity and Compton temperature does not show any Fe XXVI but only Fe XXV absorption, thus suggesting the importance of ionisation effects.

<sup>2</sup> The majority of the low energy absorption lines detected in these LMXB

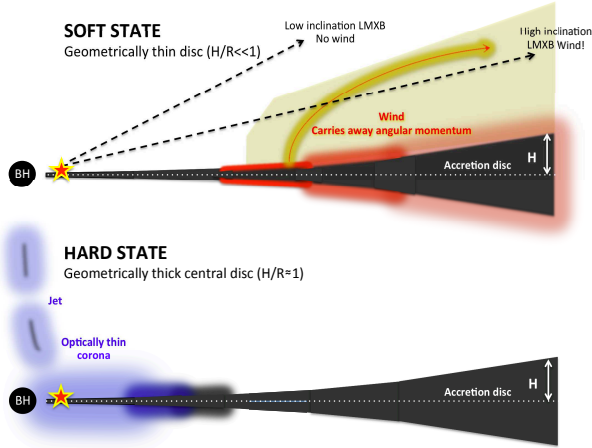
This difference in behaviour can be easily understood if both the high and low inclination sources have the same wind present in soft states and absent in the hard states, but the wind is concentrated in the plane of the disc; thus our line of sight intercepts the wind only in high inclination sources. If this idea is correct, we expect that deeper observations of low inclination sources may reveal the presence of the wind through the detection of weak ionised emission lines.

Is it theoretically plausible for the disc winds to have a strong angular dependence? Indirect evidence for an angular dependence of the wind in GBH was already inferred from the lack of emission lines associated with the X-ray absorption lines (Lee et al. 2002; Miller et al. 2006). This suggests that the wind subtends a small fraction of  $4\pi$  sr. Moreover, disc wind models and magneto hydrodynamic simulations predict a strong angular dependence of the wind (Begelman et al. 1983a,b; Melia et al. 1991; 1992; Woods et al. 1996; Luketic et al. 2010; Proga et al. 2002). In fact, if the disc wind is produced by X-ray irradiation (i.e. Compton heating, line driving), it is expected to be stronger in edge-on sources simply because once the material is lifted from the disc, it will experience an asymmetric push from the radiation field of the central source. Flattened disc winds have also been assumed to explain the winds of broad absorption-line QSO and other AGN outflows (e.g. Emmering et al. 1992; Murray et al. 1995; Elvis 2000).

#### 4 IONISATION EFFECTS

The strong connection between winds and source states requires an explanation. Ueda et al. (2010), during oscillating X-ray states

(Miller et al. 2004) are consistent with being produced by the interstellar medium (Nowak et al. 2004; Juett et al. 2004; 2006). Most of the remaining structures are consistent with being at rest, thus unlikely associated to the FeK wind (Juett et al. 2006).

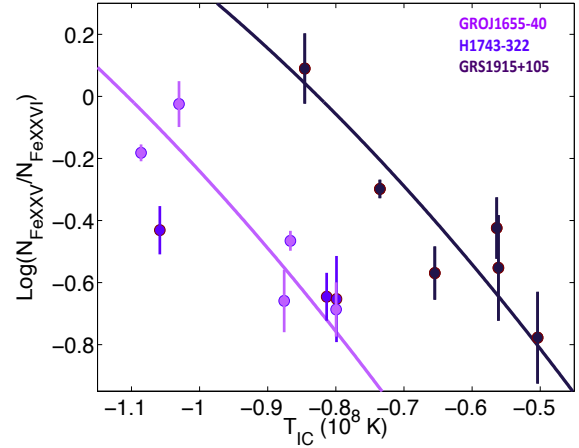


**Figure 3.** Several physical mechanisms can explain the properties of the observed equatorial disc winds. Here the thermal winds scenario is sketched. In soft states, associated with geometrically thin discs, the central source does probably illuminate the outer disc and thus it might heat it, increasing the thermal pressure that then drives away a wind, which is flattened above the disc. Thus, only in high inclination sources our line of sight to the central source crosses the wind, allowing us to detect it. In hard states a geometrically thick and optically thin corona and the jet are present, while no wind is observed.

of GRS1915+105, observe the ionisation parameter of the wind to vary with the source luminosity, suggesting the importance of ionisation. Can an over-ionisation effect explain the disappearance of the wind during hard states? If the absorber is in the form of “static” clouds with approximately constant density  $n$  and distance  $R$  from the ionising source and assuming that the spectral shape changes have a minor impact on the ionisation state of the wind, then the absorber ionisation parameter  $\xi$  will be directly related to the source luminosity<sup>3</sup>:  $\xi = L/nR^2$ . The left panel of Fig. 2 shows that *at the same luminosity* the winds are present in the soft but not in hard states (see also Lee et al. 2002; Miller et al. 2006b; Blum et al. 2010; Neilsen et al. 2011). Thus, the “static absorber” interpretation may be unlikely.

Early works on accretion disc theory (Shakura & Sunyaev 1973) already predicted the formation of winds from the outer disc. Compton heated winds (see Fig. 3) can be launched if the inner disc is geometrically thin and thus the central source can illuminate and heat the outer disc, creating a hot outflowing disc atmosphere with temperature  $T \sim T_{IC} = \int_0^\infty h\nu L_\nu d\nu / 4kL \sim 10^{7-8}$  K (Begelman et al. 1983a,b; Woods et al. 1996) whose ionisation parameter is expected to be primarily linked to the Spectral Energy Distribution (characterised by  $T_{IC}$ ) of the illuminating source.

Assuming that the Fe XXV and Fe XXVI absorption lines are unsaturated and on the linear part of the curve of growth, we can estimate the Fe XXV and Fe XXVI ion abundance (see formula 1 of Lee et al. 2002). Fig. 4 shows the Fe XXV and Fe XXVI ion abundance ratio as a function of  $T_{IC}$  for all the observations in which the two lines are detected. For all sources we systematically observe the lower ionisation states (Fe XXV) at low  $T_{IC}$  with the ratio Fe



**Figure 4.** Fe XXV and Fe XXVI ion abundance ratio as a function of  $T_{IC}$ . For each source the Fe XXV/Fe XXVI ion abundance ratio is decreasing with  $T_{IC}$  (which is a tracer of the spectral hardness). This suggests that the wind ionisation increases with spectral hardness, thus suggesting that ionisation effects play an important role here. The solid lines show the expected relation between ion ratios and  $T_{IC}$  assuming a linear relation between  $\xi$  and  $T_{IC}$  ( $\xi = \Xi \times T_{IC} / 1.92 \times 10^4$ , where  $\Xi = F_{ion} / nkTc$ ,  $F_{ion}$  is the ionising flux between 1 and  $10^3$  rydbergs; Krolik et al. 1981) and the ion fraction vs.  $\xi$  as computed by Kallman & Bautista (2001; see their Fig. 8) for an optically thin low density photo-ionised gas ( $\Gamma = 2$ ).

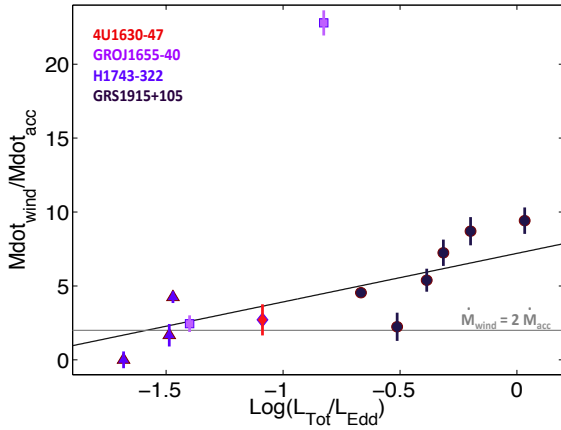
XXV/Fe XXVI decreasing for harder spectral shapes (higher  $T_{IC}$ ), as expected if the ionisation parameter ( $\xi$ ) increases linearly with  $T_{IC}$  (see solid lines in Fig. 4). This result suggests that, during the soft states, ionisation effects might play an important role in determining the properties of the wind. However, this conclusion is based on the ionisation balance for a low-density gas illuminated by a  $\Gamma = 2$  power law; in order to verify the disappearance of the wind in hard states as due to over-ionisation, a detailed study of the actual ionising spectra and wind densities would be required. Although important, this is beyond the scope of this paper. Alternatively, the wind disappearance in the hard state might arise from the fact that illumination of the outer disc is critical for the production of Compton-heated winds or from some other phenomena (e.g. organisation of magnetic field) which is related to the accretion states. Irradiation only occurs when the outer disc subtends a larger solid angle than the inner flow. Thus, the formation of thermal winds might be prevented if harder states are associated with thick discs that, even if optically thin at the centre, have an optically thick region with  $H/R \sim 1$  or have a significant optical depth as seen from the outer disc (see also Neilsen et al. 2011b). Alternatively, if the disc ionisation instability is at work in these transient sources, the Compton radius of the wind might lie in a low-temperature, and thus un-flared, part of the outer disc (Dubus et al. 2001).

## 5 DISCUSSION

How important are these winds for the accretion phenomenon? We estimate the wind mass outflow rate using the equation:

$$\dot{M}_{wind} = 4\pi R^2 n m_p v_{out} \frac{\Omega}{4\pi} = 4\pi m_p v_{out} \frac{L_X}{\xi} \frac{\Omega}{4\pi}; \quad (1)$$

<sup>3</sup> Where  $L$  has been computed as the integral of the disc emission (in the 0.001-100 keV band) plus the power law (1-100 keV) one.



**Figure 5.**  $\dot{M}_{\text{wind}}$  over  $\dot{M}_{\text{acc}}$  vs. luminosity. Apart from the one observation at the lowest luminosity, all detected winds carry away at least twice more mass than the one accreted into the central object. This implies that these winds are major players in the accretion phenomenon. The largest  $\dot{M}_{\text{wind}}$  is measured for the GROJ1655-40 observation during which a magnetically driven wind was detected (Miller et al. 2006a; Miller et al. 2008; Kallman et al. 2009).

where  $m_p$  is the proton mass,  $v_{\text{out}}$  the wind outflow velocity and  $\Omega$  is the solid angle subtended by the wind. *Chandra* observations provide reliable measurements of the outflow velocities, the detection of the wind in each soft state spectrum suggest a high filling factor, moreover we measured a wind opening angle of  $\sim 30^\circ$ , thus, once estimated the ionisation parameter, we can measure the mass outflow rate and compare it to the mass inflow rate (assuming an efficiency  $\eta = 0.1$ ). We estimate the ionisation parameter  $\xi$  from the Fe XXV / Fe XXVI ion ratio and assume the ion vs.  $\xi$  distribution computed by Kallman & Bautista (2001) and obtain values between  $\text{Log}(\xi) \sim 3.5 - 4.2$ . However, we caution the reader that these values might change significantly once (instead of assuming the ion abundances of Kallman & Bautista 2001) the ion abundances vs.  $\xi$  are computed using the properly tailored ionisation balances from the self consistent SED<sup>4</sup>. Figure 5 shows that the mass outflow rates carried away by these winds are generally several times, up to 10-20 times, higher than the mass accretion rates as found by Neilsen et al. (2011a). This indicates that these winds are fundamental components in the balance between accretion and ejection, and that disregarding such winds would mean overlooking the majority of the mass involved in the accretion phenomenon. Such massive winds suggest a higher mass transfer rate from the companion than is generally assumed. This might imply, for example, more rapid evolution of the binary orbit than we expect.

Such winds should have a major impact on the physics of the inner accretion disc. For example, it is expected that the onset of the wind would reduce the local accretion rate. After a viscous time, this would modulate the accretion rate in the inner disc and, thus, the source luminosity, ultimately producing oscillations (Shield et

al. 1986; Melia et al. 1991). Interestingly, a *Suzaku* observation caught GRS1915+105 in transition from the hard ( $\chi$  state) to the soft state (Ueda et al. 2010, but see also Neilsen et al. 2011) and, in agreement with this interpretation, both the rise of the wind and oscillations ( $\theta$  state) are observed. We note that Compton heated winds are predicted to be powerful only at luminosities higher than few per cent of the Eddington limit. This corresponds to the only range of luminosities in which the soft states are observed, suggesting a strong connection. We speculate that the wind might have an effect in keeping the thin disc stable and the source firmly in the soft state, basically preventing the transition back to the hard state until the wind is not powerful anymore. This would lead to a more or less constant luminosity for soft to hard state transitions, which is observed (Maccarone 2002). It is critical to establish in the future whether these winds really are driven by Compton heating and what their influence is on the inner accretion flow, to better understand how they are linked to the accretion state and/or the formation/suppression of the jet.

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<sup>4</sup> For example, under various assumptions about the gas density, different authors studying the same dataset found ionisation parameters that vary by  $\sim 2$  orders of magnitude (Miller et al. 2006a; 2008; Netzer 2006; Kallman et al. 2009). However, our estimated ionisation parameters here are within the typical range of measured values, and we believe they are useful for our purposes here.

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